Development of a high-power coherent THz sources and THz-TDS system on the basis of a compact electron linac

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Outline

1. Introduction
   - What’s THz?
   - Motivation of our work
2. THz Generation and Application with the Accelerator
   - THz Coherent Radiation
   - THz Imaging and THz-TDS system
3. Experiment
   - S-band Linac at AIST
   - Characteristics of Coherent Transition Radiation
   - Results of THz-TDS System
4. Summary
**THz Wave**

Terahertz wave (THz wave) is electromagnetic wave located between radio frequency and infrared light.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>0.1 THz ~ 10 THz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>3 mm ~ 30 μm</td>
</tr>
</tbody>
</table>

Terahertz wave (THz wave) is electromagnetic wave located between radio frequency and infrared light.

**Security**

Jefferson Lab.
Science Vol. 297,
2 Aug. 2002

**Quality Inspection**

AIST
Nucl. Instr. and
Meth. Vol. 637,
1 May. 2011

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*Advanced Industrial Science and Technology (AIST) & Waseda Univ. Washio Lab.*
Motivation

Identification of illegal drugs and explosives hidden in envelopes for security field using THz radiation.

Why THz ?

• Explosives and drugs have a characteristic THz spectrum
• THz wave transmits through papers, envelopes and plastics

Our Research

• High power THz source
• Development of spectroscopy system
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THz Coherent Radiation

High Power THz Coherent Radiation

The electron bunch is compressed to less than 1ps with magnetic bunch compressor.

Incoherent Radiation (bunch length > wavelength)

\[ I_{inc} \propto N \]

Coherent Radiation (bunch length < wavelength)

\[ I_{coh} \propto N^2 \]

\[ I_{coh} = (1 + (N - 1)f(\omega))I_{inc}(\omega) \]

\[ f(\omega) = e^{-\frac{(\omega \sigma_z)^2}{2}} \]

Intensity

P : Intensity of Synchrotron Radiation
N : Number of electrons

N = 6 \times 10^9 @ 1nC

~ \times 10^9 \sim 10

Electron bunch

P: Intensity of Synchrotron Radiation
N: Number of electrons

Intensity

\[ I_{coh} = (1 + (N - 1)f(\omega))I_{inc}(\omega) \]

\[ f(\omega) = e^{-\frac{(\omega \sigma_z)^2}{2}} \]
Our methods for THz generation

- **CSR**
- **CTR**

Characteristics of CSR and CTR

<table>
<thead>
<tr>
<th>Generation Method</th>
<th>① Coherent Synchrotron Radiation (CSR)</th>
<th>② Coherent Transition Radiation (CTR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Source size</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Divergence</td>
<td>Large</td>
<td>Small</td>
</tr>
<tr>
<td>Polarization</td>
<td>Horizontal</td>
<td>Radial</td>
</tr>
</tbody>
</table>

THz Imaging

THz-Time Domain Spectroscopy (THz-TDS)
S-band Linac at AIST

- Klystron 20MW
- UV laser
- Photocathode RF-Gun
- Accelerate Section
- Acceleration Tubes (1.5m) × 2
- THz-CSR port × 2
- 90° Bending magnet
- THz-CTR
- Beam dump
- 45° Bending magnet
- Q-magnet

National Institute of Advanced Industrial Science and Technology (AIST) & Waseda Univ. Washio Lab.
THz Scanning Imaging with CSR

- Imitation explosive: DNT (DiNitroToluene)

○ 0.1THz Image
○ 0.3THz Image
○ 0.6THz Image

3 color THz Imaging

Absorption

Transmission

in collaboration with Central Customs Laboratory, Japan
Why do we need the THz TDS System? -for identifying materials-

The THz-TDS is based on the EO sampling methods with the pump-probe technique. The THz spectrum is obtained by Fourier transform of the measured temporal THz waveform.

- Higher spectral resolution
- Extend spectral range

Temporal Waveform

THz Spectrum

3 color THz Imaging with CSR and rf detector

Spectral resolution is limited by rf detector
Central frequency depends on the detector

THz-Time Domain Spectroscopy (THz-TDS)

The THz-TDS is based on the EO sampling methods with the pump-probe technique. The THz spectrum is obtained by Fourier transform of the measured temporal THz waveform.
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S-band Linac at AIST

<table>
<thead>
<tr>
<th>Energy</th>
<th>40MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge per bunch</td>
<td>1nC</td>
</tr>
<tr>
<td>Bunch length</td>
<td>&lt;1ps (estimated 500fs)</td>
</tr>
<tr>
<td>Rep. rate</td>
<td>1 - 50Hz</td>
</tr>
</tbody>
</table>
THz-CTR (Coherent Transition Radiation)

- We can precisely determine the spatial origin and the generation time of the THz-CTR.
- It is easy to synchronize the interaction timing between THz-CTR and probe laser.

Merits of CTR Source

$$\frac{e^2}{4\pi^3\varepsilon_0 c} \frac{\beta^2 \sin^2 \theta}{(1 - \beta^2 \cos^2 \theta)^2}$$

$1/\gamma \approx 12.5\text{mrad}$

Small divergence comparing with CSR

<table>
<thead>
<tr>
<th>Intensity [a.u.]</th>
<th>Angle [rad]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.01</td>
</tr>
<tr>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>0.1</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Al Plate

Transition Radiation

Spatial origin

THz-CTR

Al plate

Waseda Univ. Washio Lab.

National Institute of Advanced Industrial Science and Technology (AIST) & Waseda Univ. Washio Lab.
THz-CTR Electric Field Profile and Polarization

At the focus point, CTR is thought to be longitudinally polarized (called z-pol.), because electronic fields are canceled in transverse direction. (Schottky diode cannot measure the z-pol.)

TR has radial polarization

Radial Polarizer

Electric Fields
Polarization control of CTR

Radial polarization

Z-polarization

The Z-polarization is not suitable for the EO sampling method

Half Shade

Horizontal polarization

Al plate

1 cm

1 cm
When the THz-CTR and probe laser pass through the EO crystal at the same time, the refractive index of the crystal is changed by the THz electric fields.

$\Rightarrow$ The polarization of the probe laser is also changed.

We measure the intensity difference between the p- and s-polarization of the probe laser.

$\Rightarrow$ The difference corresponds to the intensity of THz electric field.

The temporal waveform is obtained with the pump-probe technique and the THz spectrum is calculated by Fourier transform.
Experimental Setup of THz-CTR-TDS

- fs laser
- THz-CTR
- Lens
- Detector
- EO-crystal
- Polarizer
- Half-shade Al plate
- Si mirror
- Al plate
- e-
- ZnTe
- thickness: 5mm

Experimental setup diagram showing the interaction of an fs laser with THz-CTR for time-domain spectroscopy (TDS) experiments.
The THz temporal waveform has been successfully obtained. The measured THz pulse length has been estimated to be about 1.6 ps (rms). It is larger than the expected value (= electron bunch length, 0.5 ps) due to the time jitter between the probe laser and THz pulse and the finite frequency response of EO crystal depending on its thickness.
THz-TDS Result

○ Sample measurement
Imitation explosive:
DNT (DiNitroToluene)

3,4-DNT

CH₃

NO₂

NO₂

Preliminary Experiment

The THz temporal waveform has been successfully obtained.
The measured THz pulse length has been estimated to be about 1.6 ps (rms).
It is larger than the expected value (= electron bunch length, 0.5 ps) due to the time jitter between the probe laser and THz pulse and the finite frequency response of EO crystal depending on its thickness.
Summary

- THz radiation has been generated using coherent transition radiation (CTR) with polarization control for THz time domain spectroscopy (THz-TDS) at AIST.

- The THz-CTR-TDS system has been constructed with EO sampling method. The THz temporal waveform has been successfully measured with this system.

- In the next step, we will reduce the jitter and optimize the thickness of the EO crystal in order to improve the measurement accuracy of this system and to extend the measured spectral range. In near future, we will apply the THz CTR-TDS system to investigation of explosives and illegal drugs.
Thank you for your attention
1shot THz-TDS using chirped probe laser

If the probe laser is chirped, the temporal waveform corresponds to the spectrum of the s-polarized laser.

The optical time delay is not necessary. ⇒ 1shot TDS
Timing synchronization system (Low-jitter)

- Probe laser is synchronized to the their mode-lock frequencies (79.3MHz : fundamental).
- Relative timing jitter between the master and the laser is
  - about 1ps (synchronized with fundamental freq. : in this experiment)
  - < 10fs. (synchronized with 36\textsuperscript{th} harmonics freq. : the acceleration frequency (2856MHz))


Measured using time domain demodulation technique with the vector signal analyzer by measuring the amplitude monitor and phase noise.

This synchronization system has been accomplished for the 150 fs laser Compton X-ray generation. It is easily to apply to the THz-TDS.
Timing Measurement

It is easily to synchronize the interaction timing between probe laser and THz-CTR.
THz Power-meter (0.1 ~ 2THz)

**VDI - Erickson Power Meters**

The VDI Erickson Power Meter is a calibrated calorimeter-style power meter for 75 GHz to > 2000 GHz applications. The sensor head has a WR10 input and VDI sells a variety of input waveguide tapers for use at high frequencies (see application note). Contact VDI for additional information.

### Submillimeter Power Meter

- **Model PM4**
  - Extremely wide bandwidth
  - Excellent input match
  - High sensitivity
  - RS232 interface

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**Specifications:**
- Input is WR10 waveguide (1.25 x 2.5 mm) with UG387 precision flange. Useful frequency response is 75 GHz through the submillimeter range, extending even to the visible.
- Sensor size is 5.1 x 4.8 x 7.6 cm. 1 m cable connects to readout.
- 1kΩ heater resistor (on the RF load) is used for DC calibration. Internal calibration check on all ranges.
- Maximum V/SQR = ±1.1 in 0.1-10 GHz band.
- Input loss is <0.15 dB at 90 GHz.
- 41/2 digit LED panel meter readout, with 4 power ranges. Maximum input power is 200 mW average.
- Analog output BNC connector on back panel. 0-10V corresponds to 0 full scale meter reading.
- RS232 data output port.
- Calibration factor adjustment of up to ±2.5% using digit switches.
- Temperature drift is compensated to <2 µV/°C.
- The sensor has a thermal time constant (8°C) of 6 seconds. For faster response, the load is heated to a nearly constant temperature using a feedback loop. When input power is applied, the heater power is reduced, and the circuit temperature changes, which is equivalent to the input power. The loop gain varies with the power to be measured, changing the response time. For highest sensitivity, no feedback is used on the lowest scale.

**Typical performance**

<table>
<thead>
<tr>
<th>Scale (mW)</th>
<th>time for 90% response</th>
<th>RMS noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>290 mW</td>
<td>0.1 s</td>
<td>~3 µW</td>
</tr>
<tr>
<td>29 mW</td>
<td>0.15 s</td>
<td>~0.3 µW</td>
</tr>
<tr>
<td>2 mW</td>
<td>1.3 s</td>
<td>0.1 µW</td>
</tr>
<tr>
<td>290 µW</td>
<td>15 s</td>
<td>0.61 µW</td>
</tr>
</tbody>
</table>

1-2 nJ/pulse/1mm × 2mm
⇒ Peak Power about 1 kW/mm² @ 1.4m point from Source point (THz Beam size at this point: about 20cm)
Theory of EO sampling method using ZnTe crystal

Phase retardation of probe laser $\propto$ Intensity of THz electric field

Probe transmission of the polarizer $T = (1 + \sin \Gamma / 2)$
($\Gamma$ is magnitude of induced phase retardation)

$$\Gamma = \frac{2\pi L}{\lambda} n^3 \gamma_{41} E_{THz} = \frac{\pi E_{THz} L}{V_{\lambda/2}}$$

$\lambda$: probe wavelength,  
$L$: crystal length  
$n$: probe refractive index  
$\gamma_{41}$: EO coefficient involved in the Pockels effect  
$E_{THz}$: THz electric field  
$V_{\lambda/2}$: half-wave voltage of about 3 kV@800nm

Phase retardation is increased with the crystal length $L$.  
But the length is limited by the phase matching and a coherence length between the THz pulse and the probe pulse.

We should determine the crystal length.
Electro optical (EO) crystal

where φ is the angle between the major ellipse axis y’’ and the y’ axis. When the phase retardation is largest with Φ=90°, the angle φ is equal to φ=45°, which means that one should set the polarization of the probe beam to be parallel to either y’ [±1,-+1,0] or z’ [0,0, ±1] for optimized EO sampling geometry.

\[ \Gamma = \frac{\Delta I}{I_0} = \frac{2\pi d}{\lambda} n_0^3 r_{41} E_{THz} \]

Electro-optic transceivers for terahertz-wave applications
Frequency Response dependence against the thickness of EO crystal

The coherence length \( l_c (= \pi/\Delta k) \) is expressed with the dispersion in the optical spectral range by

\[
l_c = \frac{\pi c}{|\omega_{THz} \left[ n - \lambda \frac{dn}{d\lambda} - n_{THz} \right]|} = \frac{\pi c}{|\omega_{THz} \left| n_{eff} - n_{THz} \right|} \]

\( c \): speed of light
\( n_{THz} \): THz refractive index
\( n_{eff} \): effective refractive index of probe pulse

THz refractive index:

\[
n_{THz} = \sqrt{(289.27 - 6f^2)/(29.16 - f^2)}
\]

\( f \): THz frequency

Coherence length of ZnTe crystal as a function of THz frequency

- Coherence length
- Frequency Response dependence against the thickness of EO crystal

THz: \( \sim 2 \text{THz} \)  
ZnTe crystal length \(< 2.7 \text{ mm}\)
Bunch Compression

The head and tail of the bunch correspond to high-energy and low-energy parts, respectively.

The high-energy and low-energy electrons pass along the long path and the short path respectively after optimising magnetic fields of Q-magnets for the bunch compression.
RMS Bunch Length Monitor

Beam Position Monitor (BPM)

\[ \sigma[\text{ps}] = 23.7 \times \sqrt{\ln \left( \frac{V_1}{V_2} \right)} \]

\[ \sigma_t = \sqrt{\frac{2}{\Delta \omega^2} \ln \left( \frac{|F_1(\omega_1)|}{|F_2(\omega_2)|} \right)} \]

\[ \Delta \omega^2 = \omega_2^2 - \omega_1^2 \]

\[ \omega_2 > \omega_1 \]
**Theoretical THz CSR generation**

Synchrotron radiation less than critical frequency $\omega_c$ is coherently emitted from a ultra short electron bunch ($\sigma_z$). Its frequency is expressed by

$$\omega_c = \frac{\pi c}{\sigma_z}$$

The total photons ($I_{tot}$) with both of incoherent and coherent radiation are derived from equations

$$I_{tot} = I_{inc} \left(1 + (N - 1) f(\omega)\right)$$

$$f(\omega) = e^{-\frac{(\omega \sigma_z)^2}{2}}$$

$I_{inc}$: photos of incoherent radiation

$N$: number of electrons in the bunch

$f(\omega)$: fourier transform of the longitudinal electron density with Gaussian bunches($\sigma_z$)

Enhancement factor of CSR as a function of frequency by changing electron rms bunch length (500 fs, 300 fs, 100 fs, Incoherent radiation)
THz Detector (Schottky Diode)

Scanning electron micrograph of a planar Schottky barrier diode. Chip dimensions approximately 180x80x40 μm

Tunerless Design
No bias required
No mechanical tuners
NEP: 1E-11 W/√Hz (typ.)
Responsivity: 1500 V/W (typ.)
Input: WR-3.4 (UG-387/UM)
Output: 2.9mm Coax
Shown with optional horn antenna
σ_{min} = 500fs
Spotsize_{min} = 100um
Second order, Third order effect

A path length difference for particles with a relative energy deviation $\delta$ is given by:

$$\Delta z = \eta \delta = R_{56} \delta + T_{566} \delta^2 + U_{5666} \delta^3 \ldots$$

$\eta$ : longitudinal dispersion
$\delta$ : relative energy deviation ($= \Delta E/E$)
$R_{56}$ : linear longitudinal dispersion
(leading term for bunch compression)
$T_{566}$ : second - order longitudinal dispersion
$U_{5666}$ : third - order longitudinal dispersion
Possibility of Donuts profile

①Radial Polarization

②Azimuth Polarization

M. Endo, Radial Polarization
http://teamcoil.sp.u-tokai.ac.jp/kenkyu/Resonator/Radial/

FEASIBILITY TEST OF LASER-INDUCED SCHOTTKY-EFFECT-GATED PHOTOCATHODE RF GUN

CTR with radial polarizer has also the donuts profile
**THz Spectral Splitters**

![THz Spectral Splitters Image]

**Fig.1 Reflection of NIR-THz spectral splitter (two types of substrate).**

<table>
<thead>
<tr>
<th>Type</th>
<th>NIR-THz spectral splitter</th>
<th>MIR-THz spectral splitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material of substrate</td>
<td>HRFZ-Si</td>
<td>THz-grade crystal quartz</td>
</tr>
<tr>
<td>Dimensions tolerance, mm</td>
<td>+/-0.25</td>
<td></td>
</tr>
<tr>
<td>Clear aperture, %</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Surface quality, scr/dig</td>
<td>60/40</td>
<td></td>
</tr>
<tr>
<td>Surface accuracy, mm</td>
<td>+/-0.01 deviation from ideal plane</td>
<td></td>
</tr>
<tr>
<td>Coating</td>
<td>High-reflection dielectric coating (R&gt;90%) @ 730-860 nm</td>
<td>High-reflection dielectric coating (R&gt;90%) @ 9-11 μm</td>
</tr>
<tr>
<td>Angle of incidence, arc. grad.</td>
<td>45</td>
<td></td>
</tr>
</tbody>
</table>

The following THz spectral splitters are available from stock:

<table>
<thead>
<tr>
<th>No.</th>
<th>Diameter</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.4 mm</td>
<td>1.0 inches</td>
</tr>
</tbody>
</table>

**Fig.2 Transmission of NIR-THz spectral splitter (two types of substrate).**
No sample

3,4DNT

PTFE

Intensity [V]

Time [ps]

Intensity [a.u.]

Frequency [THz]

Intensity [a.u.]

Frequency [THz]

No sample

3,4DNT

PTFE

Intensity [a.u.]

Frequency [THz]

Intensity [a.u.]

Frequency [THz]

National Institute of Advanced Industrial Science and Technology (AIST) & Waseda Univ. Washio Lab.
**CSR electric field profile**

The divergence of THz-CSR

\[
< \theta^2_{\text{rad}} >^{1/2} \sim \frac{1}{\gamma} \left( \frac{2\omega_c}{\omega} \right)^{1/3}
\]

About 142 mrad

From Miho Shimada  CSR and Beam dynamics  OHO Seminar(2008)

The size of THz-CSR is about 20 cm at the THz window. (> the size of beam pipe)
Confirming CSR

\[ P \propto C^2 \]

\[ C \propto N \]

\[ P \propto N^2 \]

\[ I_{coh} \propto N^2 \]

Electron charge vs Power of 0.1 THz radiation